imaging spectrometer using a liquid crystal tunable filter

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ABSTRACT

A demonstration imaging spectrometer using a liquid crystal tunable filter (LCTF) was built and tested on a hot air balloon plat form. The LCTF is a tunable polarization interference or Lyot filter[1]. The LCTF enables a small, light weight, low power, band sequential imaging spectrometer design. An overview of the prototype system is give.n along with a description of balloon experiment results. System model performance predictions are given for a future LCTF based imaging spectrometer design. System design considerations of LCTF imaging spectrometers are. discussed.

1. INTRODUCTION

An imaging spectrometer is a sensor that collects radiometrically accurate images in many contiguous spectral bands[2]. It produces an image cube with two spatial dimensions and one spectral dimension. The three basic types of imaging spectrometers are classified by the way the image cube is collected. The whisk broom design uses line arrays to collect sets of spectral data for sequential spatial pixel samples; producing data that is naturally band interleaved by pixel (BIP) format, The pushbroom design uses area array detectors to collect a set of spectral data for an entire line of spatial samples; producing a format that is naturally band interleaved by line (BIL) format. The framing camera, uses area arrays to collect a two dimensional image in sequential spectral bands; producing a natural band sequential image. (BSQ) format. This paper introduces a framing camera type imaging spectrometer based on a liquid crystal tunable filter (LCTF).

In the past, multispectral imagers have been built that place a limited number of bandpass filters in the optical path of an imaging camera. These sensors were not considered imaging spectrometers due to their limited number of spectral bands, Recently, tunable filters have. been developed that avoid this limitation. They include the acousto-optical tunable filter (AOTF) and the liquid crystal tunable filter (LCTF). The main advantages of the AOTF include tuning speeds on the order of microseconds and very narrow spectral resolution over a wide range of wavelengths. The disadvantages include the requirement for a RF generator, limited choice in spectral resolution versus throughput track-off, and image. distortions that vary with wavelength. The LCTF compares favorably to the AOTF in all categories. In general, LCTFs are compact, capable of large apertures and a large optical field-of-view, have. low wavefront distortion, require low power, and provide random access electronic tuning with millisecond tarring speeds. The bandwidth is generally constant in wave.number space, although limited bandwidth tuning is feasible.

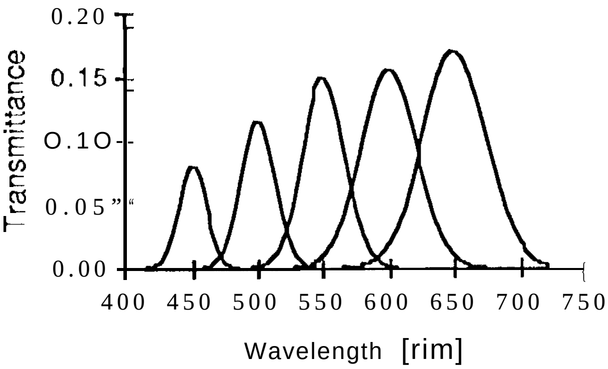
An LCTF imaging spectrometer takes advantage of these attributes in that compact, low mass, low power, robust designs are possible. The prototype design presented here. was developed in less than one month and yet flew on three days of balloon flights in extremely cold weather without failure.

2, PROTOTYPE SYSTEM DESIGN

2.1 LCTF description

The LCTF is a Lyot-type polarization interference filter that uses liquid crystals to continuously vary the. retardance of individual filter stages. A balk retarder, such as quartz, is used along with the liquid crystal to double the. overall retardance of each successive stage. The result is a narrow band filter that is electrically tunable over a wide spectral range..

The filter used in this experiment is a prototype six- stage device developed by Cambridge Research, Inc.. in support of a Small Business Innovative Research Contract[3], It has a spectral range between 430 and 680 nanometers. Figure 1 shows the band shape of the, filter for selected wavelengths. The transmittance ranges between 8% and 17% for unpolarized light. The bandwidth of the filter, varies between 30 and 50 nm, as shown in Figure 2, and is quadratic function of wavelength. The clear aperture of the device is 18 millimeters and is about as thick as it is wide. The optical quality is better than tenth wave as measured at 633 nm. The ficki-of-view is 6 degrees; it is defined as the half-angle at which the c.enter wavelength shifts by one-tenth of the filter bandwidth.



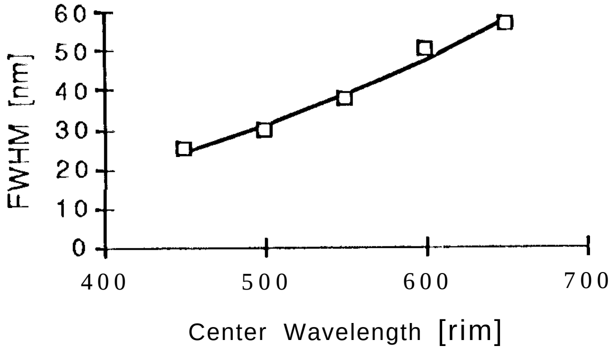


Figure 1, Band shapes of 6-stage LCTF filler tuned to 4S0, 500,550,600 and 650 nanometers. Transmittance is for unpolarized light.

Figure 2. Curve fit of full width at half maximum bandwidths of 6-stage prototype LCTF.

The tuning of the six filter stages is coordinated by an embedded micro-processor using look-up table values. Intermediate wavelength values are interpolated to yield continuous tuning. Temperature compensation is achieved by adjusting these values to null out temperature dependent retardance in the. liquid crystal and bulk quartz. Tuning is 50 milliseconds for random access between any two filter wavelengths. Command of the filter is through an RS-2.32 interface, using a simple command language.

2.2 **Prototype** imaging **spectrometer** description

The hot air balloon platform and operational constraints made necessary a simple, robust design. Ambient temperatures during flight were expected to be as low as -2.0 °C. A gasoline powered generator supplied up to 2 amps of 110 volt, 60 cycle power. Because future flights without the generator were planned, all equipment was expected to operate from batteries as Well.

A layout of the LCTF camera head assembly is shown in Figure 3. The LCTF is mounted in front of a monochromatic Sony XC-77 CCD video camera with a 50 millimeter Nikkor lens. The camera electronics are configured for linear response to light with automatic gain control and gamma disabled, The field-of-view is 7.1 by 9.4 degrees. An electric heating pad wrapped in a thermal blanket kept both the camera and LCTF above their respective 5° C low temperature operation limits. The remainder of the system electronics were packed in a small duffel bag.

The block diagram for the system is shown in Figure 4. An HP 951.X palmtop computer running a BASIC program is used to initialize the filter, command a sequence of LCTF center wavelengths, and to write ancillary data to a Horita SCT-50 video titler. The signal from the CCD camera is passed through the video tiller so that the current LCTF wavelength appears in the corner of the video image,. The video signal is recorded on a Sony GV-M20 8 millimeter video tape recorder (Vrl 'R). The VTR also provides an LCD image display which is used when adjusting the camera lens aperture, focus, and pointing. The total system mass is 4.5 Kilograms, The power consumption of the system, not including the electric healing pad is 16 watts, 10 milliwatts of which is dissipated in the LCTF.

The command program steps the filter between 430 and 680 nanometers in 10 nanometer increments, first quickly covering the range. in about 2 seconds, and then more slowly, covering the range in about 20 seconds The fast-slow cycle is repeated until interrupted by command. This provides multiple opportunities to focus, adjust the aperture, and point without having adjust system electronics or enter further commands. Wavelength, time, temperature and cycle number are continuously updated to the video titler.

After flight, the video images are digitized using a Scion LG-3 frame grabber card in a Macintosh IIx computer and processed using *Image*, an National Institute of Health developed software package[4].

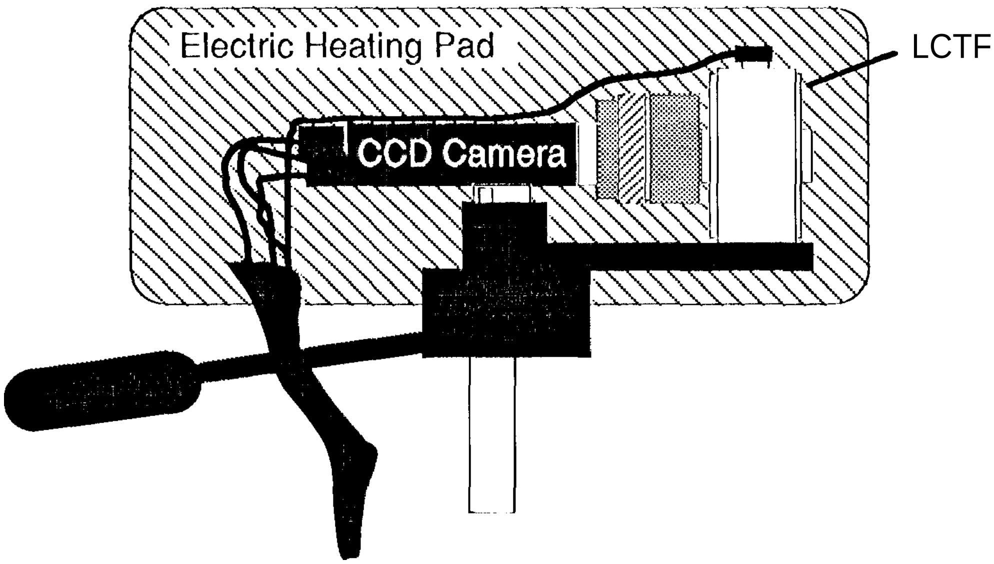


Figure 3. Layout of LCTF camera head assembly

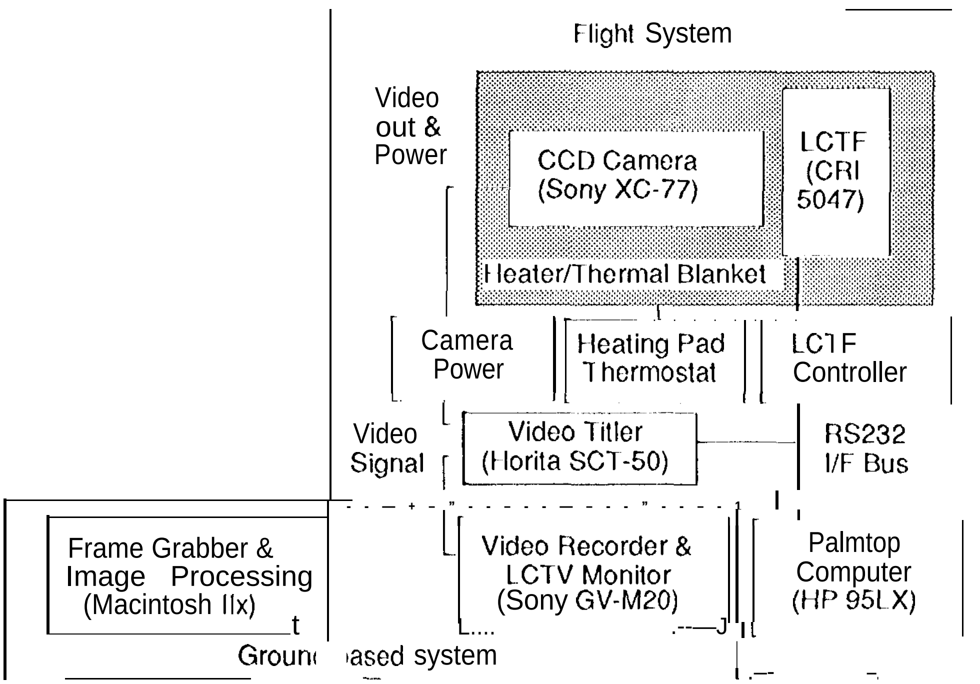


Figure 4, Prototype LCTF imaging spectrometer block diagram

3. BALLOON EXPERIMENT RESULTS

3.1 Flight operations

'1 'he hot air' balloon experiment was designed to demonstrate the feasibilit y of using hot air balloons for military and scientific test appl ications. It consisted of flying a number of experimental payloads at altitudes between 1(X) and 300 meters above. ground, Flights with the prototype LCTF imaging spectrometer were conducted on three consecutive days in January of 1993 al the Dugway Proving Grounds in Utah. Pointing was done manually because a stabilized pointing system, still under development by the Air Force, was not ready in time for the. flight,

The camera head assembly was suspended from the. gondola supcrstr'uc.lure and steadied by leaning against the rim of the gondola. Under calm conditions this lead to a point ing stabil ity of no better than one degree over a slow spectral scan cycle, The lens aperture of the camera was stopped down to f/16 to avoid saturat ion at the 570 nanometer channel. '1 'he healing pad kept the camera and LCTF at a fairly steady 25° C with external temperatures typically around -10° C. All systems performed flawlessly during flight.

3.2, Data Reduction

Dat a reduction consisted of digitizing a set of spectral channels from selected data runs and formatt ing them into a 25 layer image slack. The frames from a spectral cycle were digitized from the playback of the VTR using the wavelength title information to identify the spectral band. A spectrum was extracted from the stack by manually stepping through each layer and selecting pixel data referenced by some, spatial feature. Spectral analysis was then performed using a spreadsheet program.

3.3 Data analysis

The geometric rectificat ion of the spectral data, while. primitive, is fair] y easy to implemen t. The relationship between d i ffc.rent spectral frames can be specified by a rotation and two spatial parameters for each frame as has been demonstrated with transparencies of the image data. This technique however, dots not address changes in the seem during the spectral scan period. For example, a person walking along the tarmac during a spectral cycle is evident in one image stack, The scene motion during the. 2- second fast scans is much less of a problem.

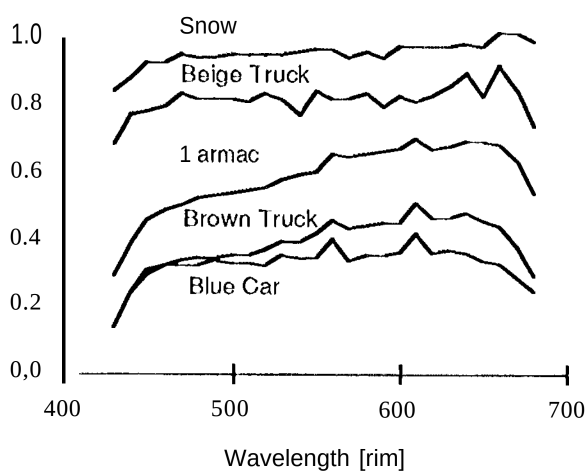


Figure 5, Reflectance spectra from targets at Michael Army Air Field.

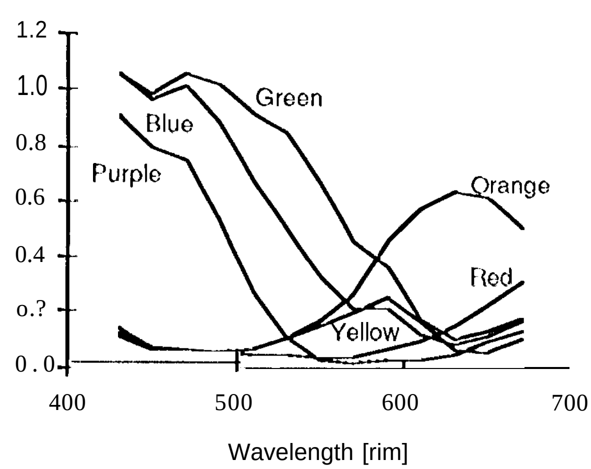


Figure 6. LCTF Reflectance spectra from color photograph image.

The calibration to reflectance is shown for dat a collected over the. tarmac at Michael Army Air Field. Data was extract cd from the roofs of three vehicles, two areas of snow, and a portion of bare concrete. Using the approximation that snow has a reflectance of unity, instrument response was calibrated by dividing by the snow response. spectrum. '1 'he results arc shown in

Figure 5. Unfortunately the available targets turned out to have relatively dull spectral features, As a c.heck reality c.heck, two separate snow areas are ratioed. Departures from unity arc attributed 10 variations in sun glint.

The dynamic range of the data is severely limited by the 8- bit digitizer. This especially limits the spectral channels with low signal level due to LCTF and camera response variations. '1 he VTR record/playback process adds scan tine pat (era noise and degrades spatial resolution. These limitations arc however, arc not fundamental to the system concept, Using an astronomy grade CCD and data system 10 match would greatly improve performance.

To demonstrate this, data was also collected from a colorful photograph used as a demonstration target, An average of 64 video frames for each spectral channel was directl y digitized in order to simulate. a higher performance system. Again, a simple calibration to reflectance was accomplished by dividing colored pixels by white pixel signal. Reflectance spectra from this image. are shown in Figure. 6.

Spectra] stability, while not directly measured in this experiment, has been investigated with periodic measurements of tile LCTF band shapes on a spectrophotometer.

4. SYSTEM MODELING

A system model of a generalized LCTF imaging spectrometer was constructed to aid in future. design efforts. Input parameters include, for LCTFs: band shape (and transmittance) versus wavelength and tuning speed; for the optics: f/number and spectral transmittance; for the detector: pixel area, quantum c. fficiency, read noise, dark current, digitization level, frame read-out rate and integration time. The input scene is a lambertian target illuminated by a 5900 Kelvin blat.kbmiy.

The model was used to predict signal to noise ratio (SNR) performance for a five nanometer resolution LCTF imaging spectrometer using commercial 1 y available components. The LCTF is modeled as a S nm bandpass filter at 5(KI nm wavelength operating from 400 to 750 rims. Peak transmission of the filter is estimated to vary in a linear fashion between 6% al 400 nm and 20% at 750 nm. F/4 optics and a 256 by 2.56 Reticon silicon focal plane array arc used to determine the remaining parameters.

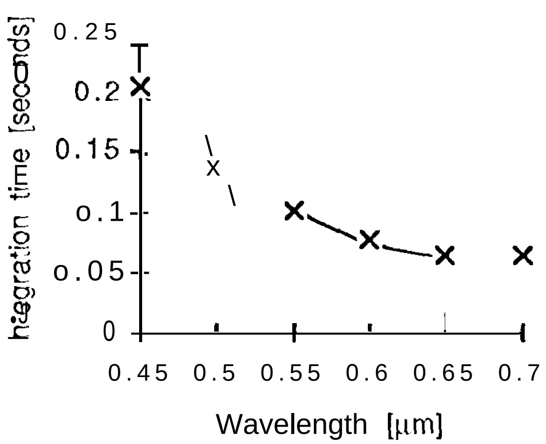


Figure 7. Integration time required to achieve constant SNR across spectrum.

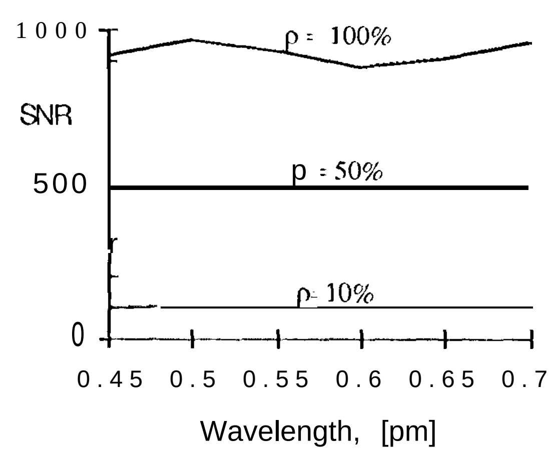


Figure 8. SNR model of 5 nm resolution LCTF imaging spectrometer for 100%, 50% anti 10% reflectance.

A unique attribute of the band sequential type of imaging spectrometer is the ability to achieve constant SNR versus wavelength by varying integration time. The system model was used 10 solve for integration time required to achieve a given SNR. The results are shown in Figure 7 along with a second order pol ynomial curve. fit, The fit was used to drive a second version of the model shown in Figure 8. The predicted performance is shown for surface reflectance values of 100%, 50% and 10%. Given the number of spectral resolution elements, integration, tuning anti frame read-out times, the model also calculates the lime required to collect tile. image cube. For this example, the image cube dimensions arc 256 x 256 spatial sample.s by 70 spectral channels and is acquired in 12 seconds.

5. DISCUSSION

Depending on science requirements and mission constraints many variations on the above design arc possible. The LCTF is not limited to a single octave of the spectrum, although throughput anti bandshape performance arc easier to optimize over segmented spectral ranges. LCTF imaging spectrometers arc, small enough 10 allow the boresighting of multiple units, each covering a portion of the required spectrum. LCTFs arc currently available that work out to 2.3 micrometers.

The random access nature of the. LCTF enables extremely high flexibility in spectral collection schemes. A fully programmable collection scheme could be quickly tailored to the needs of a wide variety of different investigators. For example, the sensor could be programmed to quickly switch in and out of absorption features to relay real-time information on the motion of atmospheric gases.

Another possible enhancement is to add a polarimeter capability to the design. A polarization beam splitter can be used to collect the light that is otherwise discarded by the first linear polarizer of the, LCTF. Another scheme would be to use a tunable half wave retarder as the first element of the LCTF and to alternate between polarization slates.

Motion within an image during the time required to collect a full image cube, is problematic with all type.s of imaging spectrometers. Band sequential imaging spectrometers can still retrieve spectra from a moving object as long as it can be identified in each monochromatic slice. Whiskbroom and pushbroom designs will distort or entirely miss a moving target during the lime required to collect all spatial samples.

While band sequential imaging spectrometers work best on fixed mounts, platform motion can be accommodated. Motion compensation, commonly proposed for spaceborne push shbroom image.rs, can be as simple as a mirror attached to the shaft of a electric motor, A gyro stabilized pointing mirror coupled with a contrast tracker would enable data collection from even a turbulent aircraft plat form. The framing camera approach lends itself well to passive motion compensation techniques. Only three parameters arc. required to correct each monochromatic frame of data, Roll and pitch translate to cross-track and down-track displacement while yaw translates to image rotation. While resampling places severe demands on radiometric calibration, framing cameras arc inherently better for geometric calibration.

6. SUMMARY

An LCTF based framing camera has been demonstrated to be feasible for usc as an imaging spectrometer. The design is simple, robust, compact, light weight, low power, and reliable. Image cubes acquired from a hot air balloon plat form were processed and spectral data was extracted. Ground data collection was used to demonstrate higher SNR spectra as a result of frame averaging, System models predict high SNR performance using commercially available components. Time varying integration can be used to achieve constant SNR across the spectrum. Active or passive motion compensation is required for usc on moving platforms.

7. ACKNOWLEDGMENTS

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8. REFERENCES

1. P. Miller, "Tunable Narrowband Birefringent Filters for Astronomical imaging," SPIE, Vol. 12,35, p. 466-473, (1 990)

2. M. Herring, T. Chrien, V. Duval and T. Krabach, "imaging spectrometry - concepts and system trade-offs," SPIE, Los Angeles, CA, January 1993.

3. NASA SBIR Contract No. NAS5-1 170 Final Report, "Tunable Liquid Crystal Filters for Remote Sensing Applications," (199]).

4. W. Rasband, National Institutes of Health.